Tiny Lasers, Huge Potentials:

VCSELs and Their Impacts to NASA and Information Technology

By Cun-Zheng Ning

What are VCSELs?

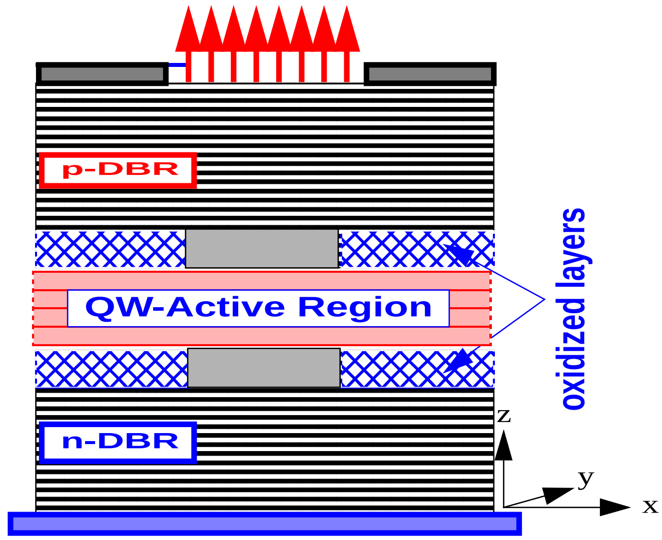

Fig.1 Schematics of a VCSEL: n-DBR and p-DBR are two stacks of semiconductor layers on both sides of quantum well active region. Typically each stack consists of 20 to 30 pairs of semiconductor layers to achieve near perfect reflection. The quantum well active region contains quantum wells of a few nanometers in thickness each. The total thickness of the device is a few microns.

Every one is familiar with lasers by now. They entered into various aspects of our lives almost 40 years ago and are still changing our daily lives constantly. Lasers come in different sizes: from those that occupy a building to those that have the size of the thickness of the human hair. In the large extreme, there is the Petawatt laser made by Lawrence Livermore National Laboratories with a peak power of quadrillion (10^15) watts. In the small extreme, there are semiconductor lasers that have output power as small as a few milliwatts. Any laser necessarily consists of two ingredients: an active material having electronic transitions that provides light emission and a cavity that provides feed-back so that light travels within it multiple times to achieve amplification. Of particular interest and noteworth are the so-called semiconductor lasers. Semiconductor lasers are based on electronic transitions involving annihilation of electrons and holes in a semiconductor, such as Gallium-Arsenide. These lasers are the smallest coherent light sources and the most efficient light converters, with an efficiency of around 50 percent from electrical to optical power. Semiconductor lasers are everywhere nowadays: from barcode scanners in supermarkets, CD player readers, to optical interconnects in the fibre communication networks. VCSELs, which stands for Vertical-Cavity Surface-Emitting Lasers, represent the most advanced semiconductor lasers, which are still at the frontiers of research and development. Vertical-Cavity means that the cavity of these lasers are vertical to the semiconductor wafer. Surface-Emitting means that the light comes out from the surface of the wafer. Fig.1 is a schematics of this device. This notation is meant to distinguish this new generation of lasers from the more traditional ones that dominated the semiconductor lasers for almost 30 years before the appearance of VCSELs about 10 year ago. Fig.2 shows difference between these two types of lasers. VCSELs are typically as small as a few microns both in diameter and in length. The properties of vertical-cavity and surface-emitting bring many advantages with such lasers: They allow a vast simplification in manufacture compared to that of edge-emitters. For example, they can be easily tested at wafer-level without further costly processing. Fabricated in quantities of up to tens of thousands per wafer is potentially feasible, which are automatically 2D arrays, as shown in Fig.3. Due to their special configuration, VCSELs have a circular beam output with very small beam divergence, as opposed to the quite elliptical beam cross section of the traditional semiconductor lasers (see Fig.2). Such circular beams with little astigmatism make them idea for both free space coupling to other optical elements and to be effectively launched into optical fibers. In addition, VCSELs have very low threshold current down to below milliampere and high bandwidth under modulation. All these unique properties make VCSELs ideal for optical interconnect applications and many other applications. VCSELs are the “transistors” of optoelectronics.

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Optoelectronics for the Tera-Era Information Technology

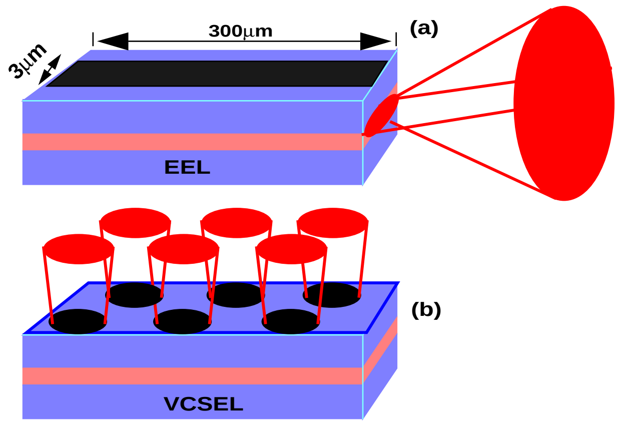

Fig.2: Comparison of a more traditional edge-emitting diode laser (EEL) (a) and VCSELs (b). Note the laser light comes from the edge of semiconductor wafer in (a) with a very astigmatic diverging beam of an elliptical cross section. In (b) light comes from the wafer surface with a much smaller divergence angle and circular beam cross section. The black areas in both (a) and (b) represent the electrical contacts which define the lasers active regions.

Optoelectronics is a field of research that deals with interactions of photons, the quantum of light, with electrons, typically in a semiconductor. Quantum optoelectronics deals with the interaction of quantized optical wave with quantized electronic wave in a semiconductor nanostructure. This is one of the few fields where quantized wave effects are already the foundation of the commercial devices. It is therefore fare to say that further progress in understandings at microscopic level will undoubtedly lead to dramatic improvement in device performance and to introduction of novel devices. One of the most important areas of application of optoelectronic devices is the information technology. The tera-ear vision of the information age (Box 1), initially articulated by J. Birnbaum of Hewlett-Packard in 1996, is a road map for the next 10 to 15 years of the information technology. Recently a panel of experts organized by the National Research Council has identified optoelectronic science and technology being the major enabling technology for each of the three areas of the information technology: from information transport, processing, to storage [1]. VCSELs as one of the most important and most advanced optoelectronic devices have important roles to play in all three areas of the information technology.

Box 1: Tera-Era Vision of the Information Technology [1]

Transport: **Terabit-per-second backbone, long-haul networks**

Access network operating at hundreds of gigabits per second
Local area networks operating at tens of gigabits per second
Gigabit per second to the desktop

Processing: **Teraoperations-per-second computers**

Terabit-per-second throughput switches
Multigigahertz clocks
Interconnections operating at hundreds of gigabits per second

Storage: **Terabyte data bank**

Multiterabyte disk drives
Tens-of-gigabyte memory chips

VCSELs and High Performance Computing

Many important applications of VCSELs in information technology, whether it is for high speed switching or data transmitting in the Local Area Network (LAN) or within a computer, are related to their function as optical interconnects based on VCSELs. Fig.4 shows how VCSEL is used as transmitter for the interconnect (lower part). The advantage of such interconnect over edge emitting diode is that VCSELs can be easily integrated with the traditional electronic devices such as transistors monolithically, as shown in the upper part of Fig.4, or heterogeneously by wafer bonding technology with com-

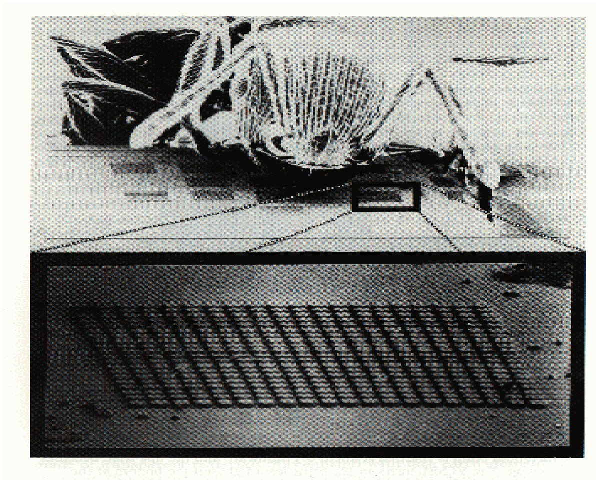

Fig.3 Upper part: An ant is looking down at VCSEL arrays. Lower Part: One of the arrays is magnified which consists of about 400 individual VCSELs. (A. Scherer, from Harbison and Nahory, Lasers, Harnessing the Atom's Light, Scientific American, 1998)

plementary metal-oxide-silicon (CMOS) circuit to form the so called Smart-Pixel Arrays (SPAs). Currently SPAs with hundreds of VCSELs have been demonstrated with a single channel speed of up to 1GHz per second, leading to a total throughput of up to 100 gigabits (GBs) per second. Such SPAs can allow integration of laser driver circuits, photodetectors, and CMOS all within very compact space area and will eventually lead to Very Large Scale Integration (VLSI) of photonics and optoelectronics integrated circuits(OEICs)[2].

The impact of VCSEL-based optical interconnects on the future of computing is many-fold. First, the multi-gigabit LAN can allow fast communication between workstations and lead to high throughput workstation clusters. The currently employed metal wire-based interconnect technology for the processor input/output (I/O) is already a speed bottleneck. The ever increasing demand for interconnect speed due to increased processor speed is met up to now by increasing number of I/O channels for a fixed per channel rate. A high-performance processor may require hundreds of such I/O channels to provide the aggregate bandwidth. The application of such VCSEL-based SPAs within a single computer as processor I/Os or other intracomputer connects can be a hugh benefit, since one single VCSEL channel can replace hundreds of metal wires. Another area of application is in the multiprocessor computers, where inter-processor communication up to10 gigabits is desired to avoid interconnect slowing-down.

VCSEL-based SPAs will be critical for high throughput board-to-board data communications required for image-processing and virtual reality applications. According to the Semiconductor Industry Association (SIA) road map projection, a 100 GBs per second throughput for a 256-bit wide bus will be realized only by the year 2010. Even then this aggregated bandwidth is still well short of what is needed for rendering the number of polygons for a high definition virtual reality application, which could require over 500 GBs per second. If VCSEL-based SPAs are used, this

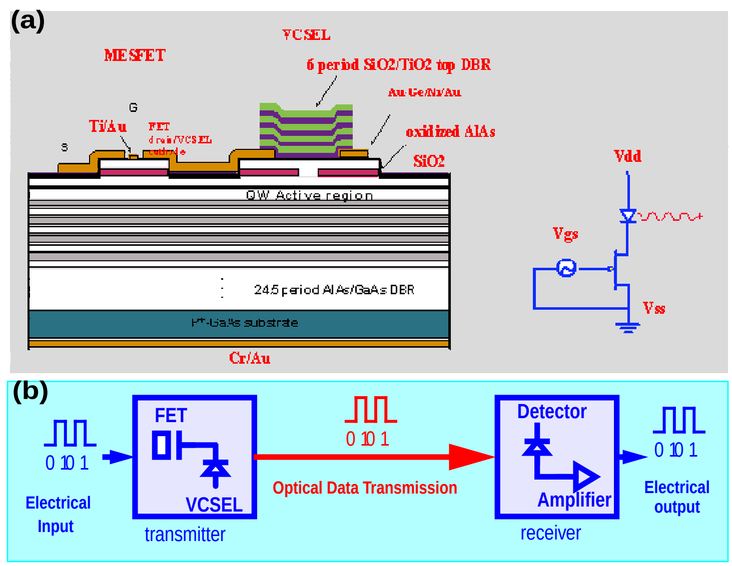

Fig.4 (a) Monolithic integration of a field effect transistor (MESFET) and a VCSEL on GaAs semiconductor (MBE group, Arizona State University). This is a key integrated device to be used for optical interconnect transmitters. In this device an input electrical signal drives the gate voltage of the FET, which drives the VCSEL. The output of this whole device is a light beam from the VCSEL which carries the electrical signal inputted to the FET gate. (b) The schematics of a VCSEL-FET integrated device-based optical interconnect: The input electrical signal is converted to optical signal through the VCSEL-FET cell. The optical signal can be transmitted through optical fiber (as in telecom or datacom) or in free-space (as inside a computer). In the receiving end (right side in (b)), the optical signal will be converted back to electrical signal.

throughput could be achievable with a 100X100 pixels of 50 MBs per second per channel. This single channel speed has already been achieved for SPAs with a few pixels. The challenge now is to achieve larger SPAs, or smaller SPAs with higher per channel bandwidth. Such SPAs are obviously very important for many NASA-related applications, for example, in large image data transmitting resulting from space explorations.

In addition, VCSEL-based high speed switching network, optical logical elements, amplifier, routing, and storage devices are also being pursued actively [3] to eventually realize all-optical digital computers. All optical computers promise many advantages, such as highly parallelism, high speed, and three dimensional architecture, but are still in the early stage of development. Whether it is all-optical computing, or the optoelectronic hybrid-computing, it seems certain that VCSELs will play the roles of what FETs (Field Effect Transistors, the fundamental building blocks of microchips) play in the current microelectronics.

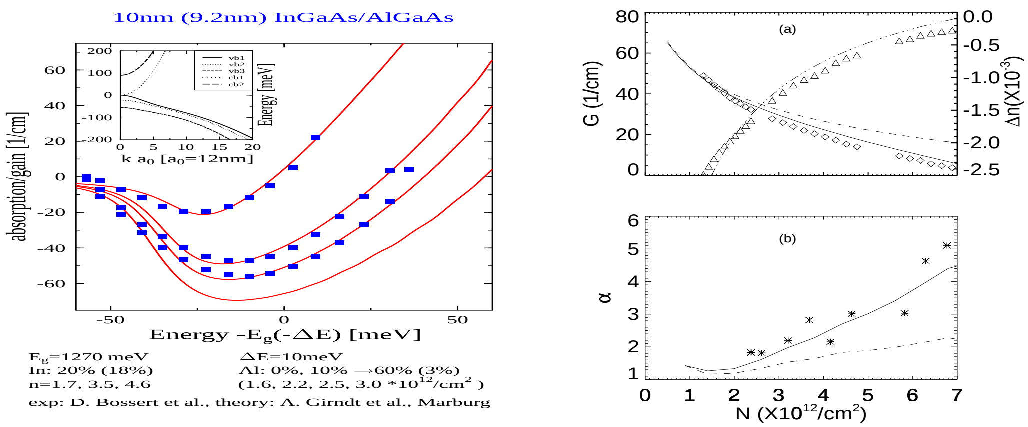

Fig.5 Comparison between experimental measurements (squares) and computer simulation (solid lines) of the optical gain spectra for a semiconductor quantum well (right hand side). The left hand side shows comparison between experiment (symbols) and numerical simulation (lines) of the optical gain (a) and the ratio of differential gain to differential index (b) at the peak gain frequency.

VCSELs in Telecom and Datacom

While the famous Moore's law says that the computer chip power doubles every 18 months, a similar law for the optical communication has been established that says the bandwidth doubles at least every year. To maintain such a speed of increase in bandwidth, both per channel speed and the number of channels need to be increased. Currently the mainstream transmitters for optical communication are based on either light emitting diodes (LEDs) or the high speed edge-emitting lasers (EELs). While LEDs have advantages of easy packaging and low cost, but lower modulation speed, the EELs have high modulation rate but are difficult to make high density two dimensional arrays. VCSELs combine the advantages of the both LEDs and EELs. The same VCSEL-based SPAs are used for telecom and data communication, both in high speed switch network and as high speed, parallel transmitters or transceivers. As the 1.3 and 1.5 micron meters VCSEL become mature and competitive, VCSELs will play more and more important role in the telecom industry.

In the area of data communications (datacom), short-wavelength (780-860 nm) VCSELs have become the laser source of gigabit Ethernet for data communications. Its inherent advantages for data communications are its single longitudinal mode, which ensures minimal chromatic dispersion, and the multi transverse mode structure, which reduces the coherence and mitigates the possibility of modal noise in multimode fiber. These lasers can transmit data at rates greater than 2 GBs per second and up to 10 GBs per second. The 10 gigabits Ethernet technology is now under active research and development in many research organizations and commercial companies. With the progress of packaging and integrtion

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technology, large VCSEL arrays with modulation speeds in the 10-GBs/s channel range will be possible. It is therefore reasonable to predict that interconnect modules using high speed VCSELs arrays will provide several hundred GBs of the total aggregated data rate.

High Density, High Access-Speed Storage using VCSELs

Currently storage density and access speed are two major issues affecting the storage and memory devices. In the purely magnetic storage systems, the best achieved density is a few bits per square micron. For the optical data-storage systems, such as CD-ROM and DVDs, the limit is usually placed by the diffraction limits of the optical spot size which is at the order of the wavelength. Even with the blue diode lasers which are still under intensive research and development, the storage density will be limited at around 10 bits per square micron. Furthermore, the drive access speed are currently limited to around 10 megabits (MBs) per second. This means considerable speed bottleneck occurs for computers operated on and beyond 300 MHz clock. Using VCSEL arrays, a group of Japanese scientists [4] has developed a two dimensional near-field optics disks. Laser light from an array of VCSELs couples to the recording medium through an array of holes of 10 nanometers in diameter. These holes provide sources of the near field that will overcome the diffraction limit and increase the storage density to 1000 bits per square microns. Assuming an array of 100 by 100 VCSELs and each being modulated at 1 Megahertz, the total array can read out data at 10 GBs per second. This will mean an improvement of 3 orders of magnitude in access speed over the current technology. While gigabit modulation of individual VCSELs is already reality, it is still a challenge to put 10 thousand VCSELs so densely together and to modulate each individual at high speed. In this respect, modeling and simulation of the dense VCSEL arrays can help to optimize the modulation speed and minimize the thermal, electrical, and optical cross-talk to study the density limit.

Other NASA Related Applications

Lasers of various kinds have been used for many different NASA missions. The huge advantages that are yet to be explored are to use as much as possible semiconductor lasers, and better, VCSELs. The use of semiconductor lasers will reduce system size, weight, and power consumption. It will simplify the mission design and reduce the overall cost. As semiconductor lasers are improved in terms of power and available wavelengths, more bulky lasers will be replaced by semiconductor lasers. For example, lasers have been already used for range finding in the Mars Orbiter Laser Altimeter (MOLA) [5] to map Mars ice cap. Currently MOLA uses the YAG lasers. There are obvious advantages to use VCSELs in the MOLA. In addition to the reduction of size, weight and power consumption, the detectors and data processing systems can all be integrated. The circular and low divergent beams from a VCSEL will allow simplifications of the optical design and increased spatial resolution.

The narrow-bandwidth emission of VCSELs-single-mode makes them uniquely suited to sense the presence of certain materials and chemicals such as oxygen or optically excitable dyes used in some medical applications. The single longitudinal mode property and the wavelength stability of VCSELs over temperature and current make VCSELs ideal candidates for systems requiring increased wavelength stability, such as pollution monitoring and interferometry. VCSEL based tunable, miniaturized spectroscopy systems could be important in space detection of certain biomolecules of astrobiological interest. The VCSEL based bioscanner currently being explored can also find important applications for astrobiology in detecting certain forms of life-significant organisms using florescent detection. The added advantage with VCSELs is that the data processing subsystems can be integrated with bid-scanner and measured data can be preprocessed before transmitted.

Computational Optoelectronics and VCSEL Modeling and Simulation

VCSEL modeling and simulation are part of a larger, newly emerging field of computational optoelectronics (COE). Just as computational electronics (CE) has been playing an important role in microelectronic industry and CFD has been doing for the aerospace industry, computational optoelectronics will be a critical capability for the optoelectronic research community and the industry. Optoelectronic industry is undergoing a profound transition from individual devices to integrated systems. As more and more devices are integrated into more and more complex systems, the need for modeling and simulation will increase significantly. Compared with CFD and CE, the physical processes involved are more complex and larger set of equations are needed to describe the systems. While several decades of research and development in CFD and CE have established comprehensive tools and capabilities, COE is still in its infancy. It is therefore an opportune time to devote resources to this immerging field of research and development. NASA Ames's hardware, software, and manpower accumulated around CFD are very advantageous in posing us to a unique position to play a leading role in the future optoelectronic information age.

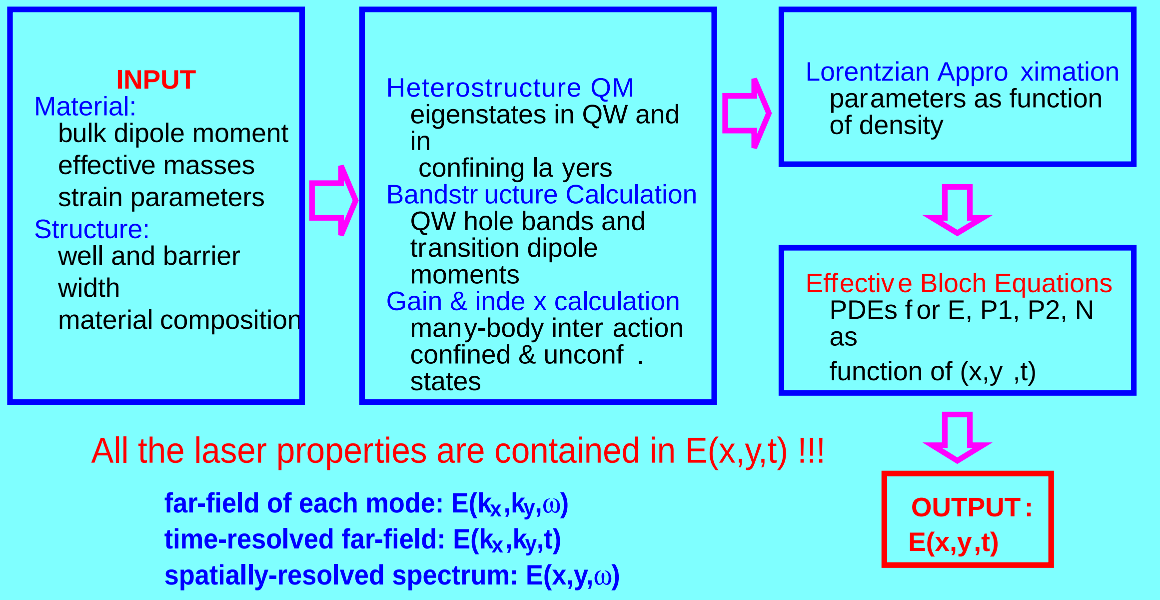
As for VCSELs, modeling and simulation play an important role in designing VCSELs with desired properties, in understanding and optimizing VCSEL performance, and in inventing novel devices. These roles are similar to what computational fluid dynamics (CFD) plays in the aircraft and spacecraft designs. While in CFD the underlying equations are the Navier-Stokes equations, the underlying equations for a VCSEL are based on quantum mechanical description of the semiconductor material coupled to laser field. For the laser field, Maxwell equation describe the laser beam propagation back and forth between the two mirror stacks (see Fig.1) in the z-direction and diffraction in the x-y plane. This is a partial differential equation first order in time and second order in space (x and y). For the semiconductor medium, there is a first-principle theory describing detailed electronic motion using the so-called quantum field theory (QFT) of solids which takes into account the nano-scale feature of semiconductor quantum struct tures. This theory allows a derivation of simplified set of equations containing, in particular, an equation for distribution function of electrons and holes. After further simplifications, a set of moment equations can be derived from the distribution function which is very analogous to the Navier-Stokes equations of CFD in terms of mathematical structures. Therefore at a certain level, VCSELs and other optoelectronic devices are described by Maxwell equation coupled to Navier-Stokes-like equations. Computationally this is more challenging than CFD, because the set of equations is larger and time scales spanning over 6 order of magnitudes are involved in optoelectronics.

Quantum Mechanical Design of Semiconductor Nano-Structures

Optical and electronic properties of semiconductors are the bases of any optoelectronic devices including VCSELs. With the progress in semiconductor wafer growth technology and in our understanding of microscopic physical processes in a semiconductor, it has become possible to engineer and design electronic properties at the nanometer scale to produce the so-called semiconductor quantum wells, wires, and dots. These are semiconductor structures with a few nanometers extension in one- (quantum wells), two- (quantum wires) and all three- (quantum dots) dimensions. This nanometer scale design and engineering allow dramatic improvements of optoelectronic device performance. In collaboration with Dr. Weng Chow from Sandia National Lab and Professor Stephen W. Koch of University of Arizona and Marburg University in Germany, Professor Jerry Moloney of University of Arizona, we have conducted research aiming to design and engineer such semiconductor structures through first-principle theory and large-scale modeling and computer simulation. Our modeling and simulation have produced very good agreement with experimental measurements. An example is shown in Fig.4. This type of first-principle simulation serves two purposes. First it makes possible for a first-principle-based computer aid design (CAD) and optimization of quantum structures before actual wafer growth. This is very analogous to the roles played by other CAD tools in mechanical system designs. The only difference is that the design rules are now the microscopic physical laws and that the involved computation is much more intensive. As a result such design nowadays is still in research stage and much more work is needed before a reliable and useful design tools can be adopted on a large scale. The second purpose of such modeling and simulation is to provide input for the next level modeling and simulation for predicting and designing the overall device performance.

Model Development: A Bottom-Up Approach to Laser Simulation

Box 2 Flow Chart for the Bottom-Up Approach in Semiconductor Laser Modeling and Simulation



The quantum mechanical design deals with optical properties of the semiconductor nano-structures. To predict laser performance, the optical properties have to be combined with Maxwell equation for the laser field. The solutions to the Maxwell equation with the proper boundary conditions and with the coupling to the optical properties of the semiconductor materials then determine the overall VCSEL performance. A fully microscopic model for such a system is described by the Maxwell-Boltzmann-Poisson-Bloch equations. This set of equations is, unfortunately too expensive computationally even with the most-up-to-date computers. It is neither necessary at this stage to attempt to solve this whole set of equations. We have developed a systematic procedure to simplify the model equations, while retaining most of important physical effects. The resulting model is what is called Maxwell-Effective Bloch Equations (MEBEs) [6]. The complete procedure is shown in Box 2. As we see there, the procedure starts from the basic, and very often known, parameters of a semiconductor structure and allows us to take into account the important Coulomb interactions and bandstructure information in our simulation. The MEBE model is much less computationally intensive. Numerical simulation of the MEBE model provides space-time resolved data for designing and analyzing laser performance.

Time Evolution of Transverse Beam Profile

Transverse mode patterns of VCSELs have significant impact for fiber coupling and for the propagation length in the fiber by reducing differential mode delay, which can drop the fiber bandwidth below desired or specified values. Optimum signal propagation distances can be achieved by engineering the output patterns of VCSELs. Modeling and simulation can be used to tailor such optimal output patterns.In our current simulation, the coupled MEBEs are solved using the finite difference method in two dimensional space and time domain with an algorithm developed by Peter Goorjian. A homogeneous grid inside a certain domain and exponentially stretching grid outside are used for our simulation. The model and the algorithm we adopt are flexible enough to handle any shapes of active region with or without refractive index guiding. Using the computer code, we have simulated various VCSELs with ring, rectangular, elliptical, or circular contacts. Fig.6 shows some representative snapshots of the near-field intensity profile in the x-y plane (compare Fig.1) for the case of a ring contact. We can see several modes of motion of the intensity patterns. First there are 8-peak (pie-type) patterns of different orientations, as are clearly seen in (c), which rotate. Then there is a ring pattern which competes with the pie-pattern dynamically. Fig. (b) and (d) show cases where the 8 peaks are visibly connected due to the strong existence of the ring mode. In the absence of the ring pattern, the pie-

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pattern rotates and the intensity of the peaks oscillate in time. Fig. (a) shows the case where the pie-pattern is week as compared to that in Fig.(c), indicating this oscillation of the peak intensity. We also find out that each time after the ring pattern reaches its maximum, the pie-pattern will change the sense of rotation from clockwise to anti-clockwise or vice versa. This type of dynamic change occurs on picosecond time scale. After average over a certain time interval, we see very often a ring pattern. The ring pattern is sometimes desirable for propagation in optical fibers. The understanding of the exact mechanisms of such dynamic competition will help us to design better transverse mode profiles. It would be very interesting to stabilize the pie-type pattern so that an array of beamlets are formed with a single laser. One of the most important issues of VCSEL based optical interconnects is the beam properties under high speed modulation. Our simulation code allows to study this issue in a straightforward manner. In Fig.7 we show time-averaged intensity patterns over 20 picoseconds (1 picosecond (ps) is equal to 10^{-12} second) for a modulation at 12 gigahertz, which corresponds to a period of 83 ps. As we see in Fig.7, the averaged pattern changes from one frame to the successive one quite drastically on the time scale of modulation. This will significantly degrade the quality of the interconnect. This is especially critical, since a simple analysis using the standard analysis without a space-resolved simulation would give a much higher bandwidth with an acceptable signal-to-noise ratio. This proves that for high speed, large aperture VCSELs, a fully space-time resolved simulation is critical in predicting and designing VCSEL bandwidth. Very often in experimental characterization of the spatial patterns in VCSELs much slower streak-camera are used to collect the spatial mode. To compare with such measurements, we shown in Fig.8 the time averaged laser intensity patterns over more than 1 nanosecond for a series of pumping levels. As we see, the individual patterns look much more regular after the average and resemble the “modes” typically measured in a large aperture VCSEL. However, it should point out that the time evolution of these “modes” on shorter time scales are much more irregular and complex than those shown in Fig.8.

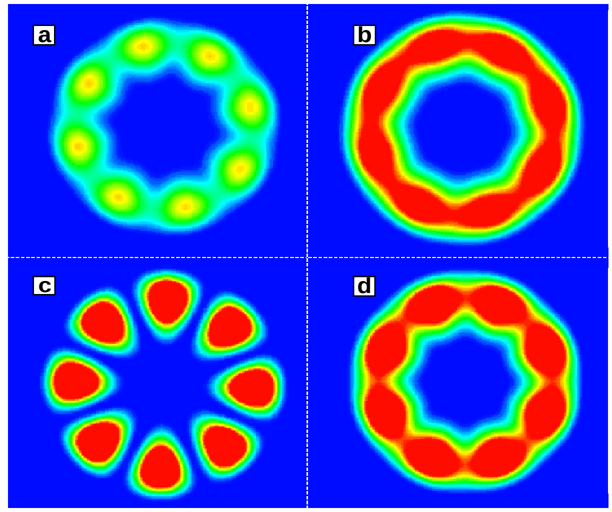

Fig.6 Snapshots of the laser intensity distribution at the VCSEL output facet for the case of a ring contact.

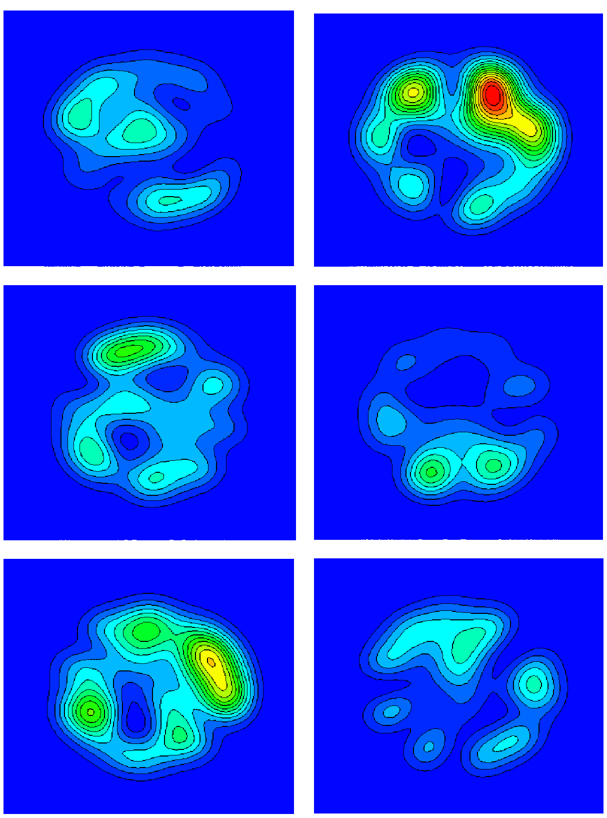

Fig.7 Near-field Intensity profile averaged over 20 picoseconds for a gain-guided VCSEL of 20 microns in diameter modulated at 12 giga hertz.

Future and On-Going Activities

As we mentioned earlier, VCSELs and other optoelectronic devices involve complicatedly

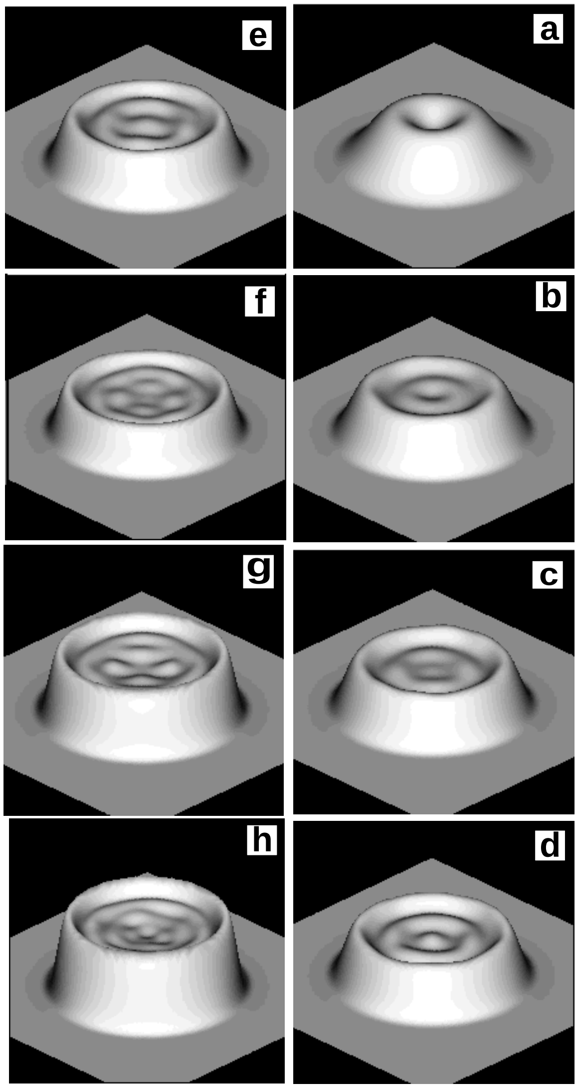

Fig.8 Near-field intensity profiles for a index-guided VCSEL of 15 microns in diameter averaged over 1.38 nanoseconds for a series increasing pumping levels from (a) to (h) (from C.Z. Ning and P.M. Goorjian, Ref.[7]).

interacting processes of optical, electronic, and thermal in nature. In our current model, only optical and part of the electronic problems have been dealt with. Electronic transport needs to be incorporated into the current modeling so that some of the artificial parameters will be removed from the model. Comparison with experiments will be more realistic. Another important issue is thermal problem. Even though semiconductor lasers have the highest efficiency among all kinds of lasers, there is about 50% of the electrical power being wasted in the form of heat. Therefore heating and lasing are coupled processes that need to be dealt with in a self-consistent way. The heating processes in a semiconductor involve a hierarchy of time scales and multiple temperatures. We are in a process of deriving a model that couples different temperatures to the rest of the laser model, so that a comprehensive, and yet computationally manageable model can be developed for VCSELs and for other opto-electronic devices in general.

To look ahead even further, the next step beyond the description and simulation of individual devices is to deal with the integrated system, i.e., OEICs. The circuit level modeling and simulation of opto-electronic devices have not drawn any series attention. As the device level modeling and simulation becomes more mature and as the demands in OEIC modeling increases, more attention and resources will be focused to this issue.

To conclude, we point out that we in optoelectronics are facing the same situation that CFD and computational electronics faced some decades ago. The optoelectronics industry worldwide grows at a phenomenal speed, mainly fueled by the insatiable demand of high speed network and communication, high speed computation, and high density storage of the information era. As the industry grows and as the devices and system becomes more and more complex, the need for design and simulation tools will continue to grow. Nowadays, modeling and simulation are already playing very important roles in aerospace and in microelectronics industries; the same will happen to the optoelectronics industry. Even restricted to NASA, optoelectronic devices, such as detectors, sensors, and laser based altimeters and interferometers are already critical elements of current space exploration. As space exploration becomes more information-technology oriented, more optoelectronic devices will be used in the future mission. The modeling and simulation tools can definitely benefit the design and discovery of higher speed, more radiation resistant, more thermally stable, more compact, and less power-consuming devices and systems for NASA’s missions.

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